

- USAEC Report TID-25951, "Reactor Shielding for Nuclear Engineers," 1973 (available from National Technical Information Service, Springfield, VA)
- *Engineering Compendium of Radiation Shielding*, International Atomic Energy Agency, Springer-Verlag, New York, Berlin, vol. 1, "Shielding Fundamentals and Methods," 1968; vol. 2, "Materials," 1975; vol. 3, "Shield Design and Engineering," 1970.

Current information on shielding, including computer codes, can be obtained from ORNL's Radiation Shielding Information Center in Oak Ridge, Tennessee. Recommendations concerning the construction of concrete radiation shields can be found in ANSI N101.6.<sup>20</sup> Also see American Society of Mechanical Engineers (ASME) Boiler Code, Section III, Division 2, "Code for Concrete Reactor Vessels and Containments."<sup>61</sup>

## 9.4 NATURAL PHENOMENA

The ability of a system to survive and function during and/or following an earthquake or tornado must be taken into consideration in the design of ESF air cleaning systems. By definition, such systems "serve to control and limit the consequences of releases of energy and radioactivity in the event of occurrences, as described in ANS 51.1<sup>34</sup> and 52.1,"<sup>35</sup> [i.e., a design basis earthquake (DBE) or tornado (DBT)]. For additional information on this subject, see Chapter 2.

### 9.4.1 NATURAL PHENOMENA HAZARDS

The natural phenomena hazards (NPH) of interest at a site are earthquakes, winds/tornadoes, floods, and lightning. Earthquakes and winds/tornadoes can lead directly to a release of hazardous materials. Floods and lightning, on the other hand, usually are not directly responsible for the release of hazardous materials, but can initiate other events such as fires or spills that lead to releases. As such, these last two events should be discussed without specific details (unless deemed necessary for a specific site). DOE Order 420.1, "Facility Safety,"<sup>71</sup> and DOE G 420.1-2, "Guide for the Mitigation of Natural Phenomena Hazards for DOE Nuclear Facilities and Nonnuclear Facilities,"<sup>72</sup> establishes the policy and

requirements for NPH mitigation for DOE sites and facilities. DOE Order 420.1<sup>1</sup> utilizes a graded approach to provide NPH protection for occupant and public health and safety, the environment, property losses, and production and research objectives. This graded approach in design, evaluation, and construction of structures, systems, and components (SSCs) varies in conservatism and rigor, ranging from normal-use building to nuclear power plant structures. DOE Order 420.1<sup>1</sup> specifies that consistent NPH requirements in a graded approach are implemented by the use of target probabilistic performance goals. Performance goals are expressed as the annual probability of exceeding acceptable behavior limits beyond which an SSC may not perform its function or maintain structural integrity. Performance goals are targeted by specifying probabilistic NPH estimates and deterministic design and evaluation methods (including intentional and controlled conservatism). Performance Categories (PC) 1 through 4 are defined with target performance goals.

DOE Order 420.1<sup>1</sup> requires use of DOE-STD-1020-2002, "Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities"<sup>73</sup> to provide design and evaluation criteria for earthquakes, wind/tornadoes, and floods. This Order also requires this standard to be used as guidance in implementing the NPH mitigation requirements. DOE-STD-1020<sup>3</sup> specifies performance goals for PC 1 through PC 4, as well as relevant hazard probabilities, to establish the design basis loads. The goals of DOE-STD-1020<sup>3</sup> are to ensure that NPH evaluations are performed on a consistent basis, and that DOE facilities can withstand the effects of natural phenomena. Considerable new information and analysis/design methods have been developed since DOE-STD-1020<sup>3</sup> was issued. As of this writing, a "draft" version of proposed changes to DOE-STD-1020<sup>3</sup> has been issued for review and comments. This version will incorporate the seismic analysis/design requirements of the International Building Code (IBC)<sup>4</sup> The final revised version of this standard is expected to be available by Spring 2002. [Note: The IBC is a commercial code written without regard to nuclear requirements. For nuclear structural analysis, please reference ASME Boiler

Code, Section III, Subsection NF, and ASME AG-1, Section AA, Article AA-4000.<sup>18</sup>

Additional guidance addressing NPH events is provided in several other DOE NPH standards:

- DOE-STD-1021-93, “Natural Phenomena Hazards Performance Categorization Criteria for Structures, Systems, and Components.”<sup>5</sup>
- DOE-STD-1022-94,<sup>6</sup> “Natural Phenomena Hazards Site Characterization Criteria.”<sup>6</sup>
- DOE-STD-1023-96,<sup>7</sup> “Natural Phenomena Hazards Assessment Criteria.”<sup>7</sup>
- DOE-STD-XXXX-XX (draft) “Lightning Hazard Management Guide for DOE Facilities.”<sup>8</sup>

## 9.4.2 EARTHQUAKE

Earthquakes differ from other natural phenomena in that there are no preliminary warnings. Emergency response must be prioritized, and few facilities will receive immediate support from the fire department or other emergency-response teams. Therefore, structural collapse, hazardous material release, fire, and other events that a low priority facility may suffer could possibly be ignored because resources are directed to higher priority facilities. Emergency response must be prioritized and will generally be directed to those locations where lives are threatened. **TABLE 9.1** shows the mean annual exceedance probabilities for the DBE for various PCs.

Table 9.1 – Seismic Performance Categories and Seismic Hazard Exceedance Levels

Performance Category	Mean Seismic Hazard Exceedance Levels $P_H$	Remarks
0	No requirements	-
1	$4 \times 10^{-4}$	Use IBC 2000, Seismic Use Group I Criteria 2/3 MCE Ground Motion
2	$4 \times 10^{-4}$	Use IBC 2000, Seismic Use Group III Criteria MCE Ground Motion
3	$4 \times 10^{-4}$ ( $1 \times 10^{-3}$ ) See Note 2)	Analysis per DOE-STD-1020 <sup>3</sup>
4	$1 \times 10^{-4}$ ( $2 \times 10^{-4}$ ) See Note 2)	Analysis per DOE-STD-1020 <sup>3</sup>

Notes:

1. For PC1 through PC 3, the  $P_H$  are based on Maximum Considered Earthquake (MCE) Ground Motion with 2 percent exceedance probability in 50 years.
2. For sites such as Lawrence Livermore National Laboratory, Sandia National Laboratory-Livermore, Standard Linear Accelerator, Lawrence Berkeley Laboratory, and Energy Technology Engineering Center, which are near tectonic plate boundaries.
3. Specific criteria regarding nuclear power plant designing for earthquakes are defined by the USNRC.

The two main steps in evaluating the impact of an earthquake for a particular facility are (1) estimate the probability of exceeding the earthquake magnitude of interest, as discussed below; and (2) estimate the damage the facility will sustain for this magnitude of earthquake. From this assessment, the consequences can be calculated. Most DOE sites are in areas of relatively low seismic activity; thus, damaging earthquakes are considered unlikely (California sites excepted). If a recent site-specific Probabilistic Seismic Hazard Analysis (PSHA) for a site is available, it should be verified because it would document the probabilistic analysis used to determine the ground motion levels and the recurrence intervals corresponding to the various sizes of earthquakes possible at the site. An example from the Pantex site (1998) shows the results of an analysis at the Pantex soil site plotted as peak horizontal ground acceleration (expressed in units of the acceleration of gravity,  $g = 9.81 \text{ m/s}^2$ ) versus the annual probability of exceedance. In the absence of a site-specific PSHA, a generic PSHA can be used, such as that given in DOE-STD-1020.<sup>3</sup>

Since the peak ground acceleration for a given PC is usually given at bedrock, an analysis must be performed to calculate the ground motion at the foundation level of the structure. Other aspects of seismic behavior of a structure must also be considered. The ground motion has characteristics that will cause different responses in structures with different frequency responses. For example, a tall slender structure will respond differently to a given ground motion than a squat massive structure. The structural response is accommodated by calculation of a characteristic response spectrum for the ground motion. This spectrum and its associated artificially generated time-history records are used to analyze the response of the structure. A PSHA should also provide surface response curves in the form of recurrence curves and surface response spectra. These curves may not be directly used to estimate recurrence because the structure may interact with the soil underneath to amplify the ground motion's response.

The earthquake problem arises from the possibility of associated malfunction of fans, dampers, filters, or other functional components of the system, or the rupture or structural damage

of pressure-boundary components (ducts, housings, fan, or damper casings) when the system is subjected to rapid, violent, repetitive shaking or dislocations, either as a lumped mass or as parts of the assembly are independently dislocated from each other. Fortunately, the physical masses of air cleaning system components are generally small in relation to the massive concrete building elements to which they are anchored. If natural frequencies are greater than about 30 Hz and the parts of any single air cleaning unit are anchored to the same building element, a satisfactory earthquake-resistant air cleaning system can be achieved fairly easily. Problems arise when portions of the same air cleaning unit (e.g., different segments of the ductwork) are anchored to different building elements that can vibrate independently. The design and design qualification of earthquake-resistant air cleaning systems is discussed below.

#### 9.4.2.1 SEISMIC DESIGN AND QUALIFICATION OF ESF AIR CLEANING SYSTEMS

External components of the system (e.g., housings, and fans) should be rigidly anchored to major building elements (walls, floors, partitions), where practicable. These building elements are sufficiently stiff to assume that interaction of the air cleaning system on the building by breaking loose when supported by building is negligible, and that the motion of the building element can be considered the only input to the system. External components of the same system should be anchored to the same building element. Where this is not possible, the motion produced in the building element experiencing the greatest motion under the influence of an earthquake should be used to determine the accelerations of all segments of the system or subsystem. When parts of the system are anchored to more than one building element, displacements of the anchor points of different parts of the system should be considered to be 180 degrees out of phase and must be added to establish the maximum stresses in connections and other parts of the system that could be affected by the combined horizontal, vertical, twisting, and bending motions caused by the earthquake. Expansion joints, expansion loops, or other means of providing flexibility while preserving the leak integrity of the system may be used where necessary. Earthquake experience shows that spring vibration isolators

for heavy components are very susceptible to horizontal motion. If vibration isolators cannot be avoided, properly designed lateral stoppers should be used to minimize horizontal displacement. Anchors, attachments, and connections between runs of duct, dampers (valves), and fans (including motor mount), must be designed to transmit the forces associated with the accelerations induced in the air cleaning system, as well as the relative distortions of the building elements to which the external components of the system are anchored. Ducts, housings (including their pressure boundary welds and flanged connections), and the filter-mounting frames and doors (including door frames) of housings should be designed to withstand, without buckling or rupture, the forces associated with equipment accelerations, related distortions of connected parts, and related distortions of the building elements to which they are anchored.

General seismic criteria for DOE facilities are provided in DOE-STD-1020.<sup>3</sup> Similar information for facilities licensed by the U.S. Nuclear Regulatory Commission (USNRC) is available in USNRC Regulatory Guide 1.100<sup>10</sup> and the USNRC "Standard Review Plan."<sup>11</sup>

### Seismic Qualification

The components should perform their intended functions and, if required by procurement specifications, should not sustain damage during and after they are subjected to excitations resulting from ground motions due to the DBE. This is demonstrated through a process called A-seismic qualification. The seismic qualification may be achieved following any one or a combination of the following methods. [Institute of Electrical and Electronics Engineers (IEEE) Standard 344<sup>12</sup> provides an excellent discussion of equipment seismic qualification procedures.]

### Seismic Motion of Component Location

The excitation level at the mounting location of the component is needed for use of any of the three qualification methods. This can be determined from a seismic analysis of the building structure supporting the component. The excitation can be described by any of the following functions.

The response spectrum provides the maximum response of a single-degree-of-freedom system as a function of the system natural frequency and damping when subjected to the input motion.

The time history displays the earthquake-induced motion as a function of time.

The power spectral density is the mean squared amplitude per unit frequency of the vibratory motion.

A response spectrum expressed in terms of acceleration over a frequency band of interest (e.g., 1 to 33 Hz) is the most commonly used and convenient function in characterizing the excitation level at the component location. This required response spectrum is used in the seismic qualification and/or compared with the qualification spectrum to demonstrate qualification.

### Structural Analysis

In general, structural analysis is a cost-effective tool to demonstrate seismic qualification. This method is applicable if (1) the target component can perform its function as long as its structural integrity is maintained and (2) the structural response of the target component can be reliably determined from analysis. In a structural analysis, structural responses such as stresses, strains, and displacements are calculated and compared with their respective allowable values, which are predetermined from material properties and component characteristics (e.g., clearance).

Structural analysis can be static, equivalent static, or dynamic. If the fundamental frequency of the component is high (e.g., greater than 33 Hz), amplification of motion through the component structure is usually negligible, and structural response can be determined by applying a static load (i.e., mass x zero period acceleration) to the component. If the fundamental frequency of the component is unknown, the equivalent static (or static efficient) method can be applied in return for additional conservatism. In this method, an equivalent static force is calculated by multiplying the mass with a static coefficient and the peak acceleration of the required response spectrum at the appropriate damping value (mass with static coefficient x peak acceleration). A damping coefficient of 3 percent is acceptable for all

components except piping. Larger damping values may be justified.

A static coefficient of 1.5 has been established from experience to account for the effects of multifrequency and multimode response for linear frame-type structures. When the use of static or equivalent static analysis cannot be justified, structural responses are determined via dynamic analysis, although at additional cost. If the structural responses of the component are less than the respective allowable limits, the component will be considered qualified provided structural integrity alone demonstrates its functional operability.

Components, or the complete system, may also be qualified by structural analysis. The objective of the analysis is to predict the stresses, displacements, and deflections that will develop in critical parts of the component or system as a result of the specified input or time-history motion applied at the base (anchor points) of the component or system. The structural model is defined by the physical properties of the system to be analyzed; its mass, stiffness, and damping characteristics; and the time-varying accelerations, displacements, and relative velocity changes introduced at its foundation (anchor points).

If the mass of the component or system to be analyzed is small compared to the mass of the building element to which it is anchored, the supported component or system may be treated as a lumped-mass, multi-degree-of-freedom system with an input at its foundation (anchor points) equal to the motion of the building element to which it is attached (i.e., no interaction is assumed).

If the natural frequency of the item (component or system) is less than 0.2 Hz or more than 33 Hz, the item may be analyzed statically. The seismic forces on each element of interest are obtained by concentrating its mass at its center of gravity and multiplying by the appropriate maximum floor acceleration. Operating live and dead loads are added to the seismic loads in their appropriate directions. Displacements may be the limiting factor and must be accounted for in the design analysis. A damping value of 3 percent is acceptable for all components except piping. Larger damping values may be justified. If the

mass of the component or system is large compared to the mass of the building element to which it is attached, or if the item is not anchored rigidly to a building element, the interaction of the system on the building element must be considered and the system must be dynamically analyzed as a multi-degree-of-freedom mathematical model. The item (component or system) may be modeled as a series of discrete mass points connected by mass-free members, with sufficient mass points to ensure adequate representation of the item as it is supported in the building structure. The resulting system may be analyzed using the response spectrum or time-history analysis technique. A stress analysis should be made next, using the inertial forces or equivalent static loads obtained from the dynamic analysis for each vibration mode. If the response spectrum analysis technique is used, the seismic design stress usually may be obtained by taking the square root of the sum of the squares of the individual modal stresses. The absolute sum of the individual stresses should be taken, however, for closely spaced, in-phase vibration modes. In the analysis, each of the two major horizontal directions is considered separately and simultaneously with the vertical direction in the most conservative manner.

The analysis must include an evaluation of the effects of the calculated stresses on mechanical strength, alignment (if critical to proper operation of the air cleaning system), and operational (functional) performance of the components and the system as a whole. Maximum displacements at critical points must be calculated, and interference or plastic deformation must be determined and evaluated.

#### Similarity Analysis

In a similarity analysis, the dynamic and physical characteristics of the component and the required response spectrum are compared with those for a component that has already been qualified. This requires the availability of a database of qualified components. Engineers who are familiar with the component design and functional requirements should establish the dynamic similarity. Databases derived from past qualification and earthquake experience exist in the literature.<sup>13</sup>

### Combination Method

By combining different elements of the various qualification methods, a hybrid method may be developed that will make the qualification practical and potentially highly cost-effective. For example, a system may be too large for a shake table, but may contain sensitive components that require qualification by testing. In such cases, the system may be structurally analyzed to determine the motions at the component locations, and these motions (e.g., expressed as response spectra) can be used as the required input motion for qualification of the components via dynamic testing. Similarly, by supplementing experience data with a simplified structural analysis, a powerful, cost-effective qualification method may be devised. Similar application has been proposed and reviewed for advanced light water reactors.<sup>14, 15</sup> This proposal includes duct qualification using a design-by-rule method—simple static analysis of linear duct models.

### Testing

Either components or a complete system may be qualified by testing under simulated earthquake conditions. For a very few select cases where the component structure is simple and its potential failure mechanism is known (e.g., binding of shaft), a static test under the application of a conservative static force may be acceptable. Otherwise, dynamic testing is required. In such cases, the specimen to be tested is mounted on a biaxial or triaxial vibration generator in a manner that simulates the intended service mounting, and vibratory motion is applied independently to each of the perpendicular axes. Displacement induced in the vertical axis should be considered equal to at least 0.67 times the displacement in the major horizontal axis. The magnitudes of horizontal acceleration and displacement are those magnitudes for which the specimen is to be qualified. Where practicable, accelerations, displacements, and relative velocity change should be the maximum that the equipment can tolerate without loss of function. For fans, motors, dampers, and other operating equipment, sufficient monitoring devices must be located on the test specimen or assembly so that the maximum response is always obtained. Tests are made at several sinusoidal frequency steps that represent the range of frequencies for which the

item is to be qualified at the natural frequency or at a number of predetermined frequencies, as discussed in the following sections.

### Exploratory Vibration Test

An exploratory test should be made first, using a sinusoidal steady-state input of low magnitude to determine the presence and location of any natural frequencies within the range of 1 to 33 Hz or the frequency range stated in the project specification. The test should be performed at a maximum sweep rate of 1 octave/min and a minimum acceleration of 0.2 g, with dwell at resonance for at least 30 sec. If no resonating frequencies are found, the item may be analyzed statically or may be tested via (1) continuous sine test, (2) sine-beat test, or (3) multiple-frequency test. If one or more resonant frequencies are found in the exploratory test, the design of the component should, if possible, be modified to move the resonating frequencies above 33 Hz or to the maximum frequency at which the item is to be qualified. If the item cannot be readily modified, a performance test should be made at the resonant frequency and at an amplitude of at least the corresponding value for that frequency from the response spectrum for the building element of interest.

### Continuous Sine Test

A continuous sinusoidal motion at the qualification frequency and the corresponding maximum acceleration is imposed for a length of time that is conservatively consistent with the service for which the item will be used. The item is operated during and after shaking to demonstrate its ability to perform its function. The test duration is specified in a detailed test procedure. The item is mounted on the vibration generator in a manner that represents its installation under service conditions. The vibratory forces are applied to each of the three major perpendicular axes independently unless symmetry justifies otherwise. Sufficient monitoring equipment must be used to evaluate performance accurately before, during, or after the test, depending on the nature of the item to be tested.

### Sine-beat Test

This test is conducted by inducing sine beats of peak acceleration corresponding to those for which the item is to be qualified, at the frequency and amplitude of interest. The duration and amplitude of the beat for each test frequency must be chosen to produce a magnitude equivalent to that produced by the particular building-element response, with appropriate damping factors. For a test at any given frequency, five beats of ten cycles per beat are normally used, with a pause between the beats so that no significant superposition of motion will result. Mounting of equipment and instrumentation shall be per approved methods.

### Multiple-Frequency Test

Multiple-frequency testing provides a broadband test motion that is particularly appropriate for producing a simultaneous response from all modes of multi-degree-of-freedom systems. The test may be performed by applying a random excitation to the component (simultaneously in each of the three orthogonal directions), and adjusting the amplitude of the excitation in a frequency band not exceeding 1/3 octave. The resulting test response spectrum should envelop the required response for qualification.

### Documentation

The selected method(s) of seismic analysis, mathematical models and their natural frequencies, and input time-histories, as well as corresponding response spectra, damping values, and allowable stress criteria, must be shown in a qualification report together with the results of all tests and analyses. If the similarity analysis method is used, the comparison, including the experience data, should be documented. The documentation must provide detail information that demonstrates the item meets specified requirements when subjected to the seismic motion for which it is to be qualified. A licensed professional engineer who is qualified in the analysis of such systems should certify the analytical and test results, including the operational data.

All instruments, including the heater, damper, and fan controls, should meet the requirements of IEEE 323, "Standard for Qualifying Class 1E Electrical Equipment for Nuclear Power

Generating Stations,"<sup>16</sup> and IEEE 344, "Recommended Practice for Seismic Qualification of Class 1E Equipment in Nuclear Generating Stations."<sup>12</sup> USNRC Regulatory Guide 1.100, "Seismic Qualification of Electrical Equipment for Nuclear Power Plants,"<sup>10</sup> and USNRC Regulatory Guide 1.105, "Instrument Set-points"<sup>17</sup> are also applicable. Instrument controls and control panels should meet the design, construction, installation, and testability criteria in Section IA of ASME Code AG-1.<sup>18</sup>

The design, construction, and test requirements of Section BA of ASME Code AG-1<sup>18</sup> apply to ESF system fans and motors. Motors must meet the qualification requirements in IEEE 334,<sup>19</sup> IEEE 323,<sup>16</sup> and IEEE 344.<sup>12</sup> The structural design of ESF air cleaning systems must consider the service conditions that the components and housing may experience during normal, abnormal, and the accident conditions. The ESF air cleaning system must remain functional following dynamic loading events such as an earthquake. The structural design of all ESF air cleaning systems, including all components, must be verified by analysis, testing, or a combination of both. Qualification criteria are contained in Article AA-4000 of ASME AG-1.<sup>18</sup> The design requirements for determining housing plate thickness, stiffener spacing, and size are contained in ASME-AG-1, Article AA-4400, "Structural Design," Section HA, "Housings," and Section SA, "Ductwork."<sup>18</sup>

### Equipment Qualification

The fundamental reasons for qualifying equipment are to provide adequate levels of safety for the life of the facility. Equipment qualification is often a requirement for an operating license. Equipment qualification is designed to provide reasonable documented evidence that the ESF system will satisfy the following three characteristics.

- Qualification goals may be generic or application specific. Generic qualification is probably best for the original equipment manufacturer because it enables use of the qualified item for a variety of applications. This type of qualification program requires test parameters that may exceed the needs of the current program, but are not extreme enough to reduce the chances of a successful qualification. An application-specific

qualification limits the use of the component or system to those having the same or reduced environmental stresses.

- A mild environment qualification can usually be accomplished without determining a qualified life (per Section 4 of IEEE 323),<sup>16</sup> whereas a harsh environment program usually requires testing to verify performance under extreme accident conditions. Simulated aging is necessary to arrive at “end of life conditions” prior to accident condition testing.
- It is necessary to determine whether the components are designated as safety-related or non-safety-related. A non-safety-related item can often be excluded from the qualification process when it can be shown that a failure of that component would not adversely affect the safety function of the overall equipment.

The qualification plan must be developed in accordance with IEEE 323,<sup>16</sup> and must include a determination of the qualification method, a listing of the environmental service conditions, a description of any required aging programs, a protocol of the test sequence, and a definition of the accident test profiles.

An aging program might consist of stressors such as thermal aging, mechanical/cyclic aging, radiation exposure, and mechanical vibration. All of these are designed to simulate conditions that would be encountered during the expected life of the test specimen prior to its’ undergoing an accident condition or test such as seismic pressure, high-energy line break (HELB), or loss-of-coolant accident (LOCA).

The requirements of IEEE 323<sup>16</sup> must be followed when preparing a qualification plan. The entire facility should be considered when designing an ESF system. Two questions must be addressed: (1) how can the system under design affect other systems and areas? and (2) how can the remainder of the facility affect this system?

There are system characteristics that apply to all air cleaning systems regardless of specific function or the nature of the facility. One is that they must be capable of continuing to meet quantifiable test criteria to provide verifiable evidence of

maintaining acceptance limits over the life of the installation. Therefore, an ability to maintain and test systems is as important as the ability of those systems to meet the initial performance criteria. The factors described in the following sections apply to all systems and must be addressed.

### 9.4.3 TORNADO

Structural damage from a tornado may arise from missiles, wind, or atmospheric pressure changes that occur when the funnel cloud passes over the building. Assuming the building is constructed to be tornado-resistant, damage to the air cleaning system will result mainly from the pressure changes that occur in the stack, ducts, and building spaces surrounding the ducts. The design basis tornado hypothesizes that pressure on the building will decrease by as much as 3 psi over a 2-sec period, remain at the depressed level for 3 sec, then return to normal.<sup>31</sup> Because the operation of a ventilation system substantially relies on stable atmospheric conditions to maintain pressure differentials between the containment zones of a building and to prevent the release of contaminants, it is likely that system upset, overrunning or reversal of fans, or even reverse flow could occur due to atmospheric depressurization, and failure of the dampers could exacerbate the condition. On the other hand, stack(s), ducts, and fans would attenuate the depressurization, and it is unlikely that filters in the exhaust system would experience the pressure differentials hypothesized by the USNRC Regulatory Guide 1.76.<sup>31</sup> Studies conducted by Anderson and Anderson<sup>21</sup> and W.S. Gregory<sup>22</sup> indicate that, unless they have seriously deteriorated, those HEPA filters that meet the requirements for nuclear service are capable of withstanding any pressure differential they are likely to experience under tornado conditions. The effects of high airflow rates, large pressure differentials, and sustained pressurization or depressurization on air cleaning systems and components are relatively unknown. The dynamic effects of tornadoes and pressure transients on air cleaning and ventilation systems need to be considered, and methods for describing, analyzing, and calculating the forces to which these systems would be subjected, along with their response to these forces, need to be mathematically modeled and developed. USNRC Regulatory Guide 1.76<sup>31</sup>



recognizes that the statistical frequency and severity of tornadoes vary from one part of the country to another and provides guidance for the application of wind speed and pressure values in particular locations.

Wind and tornadoes can potentially damage buildings and other structures in a variety of ways. Loose objects picked up by the wind can be turned into missiles that can penetrate a structure. The roof covering and siding material can be blown off the building. Winds passing sharp corners of the building tend to separate from the building, causing an outward pressure. In general, the windward surfaces of the building experience an inward pressure, and all other exterior surfaces experience an outward pressure. Likewise, the internal air pressure can rapidly change if air can pass into or out of a structure through openings such as those caused by a wind-driven missile. If the opening is on the windward side of the building, the internal pressure increases, reinforcing the outward pressure of the outside air on the other surfaces. If the opening is on any other side of the building, the internal pressure decreases, counteracting the outward pressure of the outside air. In any case, if the atmospheric pressure change (APC) exceeds the structural strength of the building, the building can suffer significant damage. The APC is especially important in tornadoes.

High-speed winds can be classified as "straight," "tornado," or "hurricane." Straight winds are nonrotating winds that cover a wide area, typically many tens of miles across, and can reach speeds exceeding 100 mph. They are generally associated with thunderstorms, mesocyclones, and orographic effects. Tornadoes are violently rotating winds that are highly localized, a few miles or less across, and can reach speeds in excess of 200 mph. They can accompany severe weather events such as thunderstorms and even hurricanes. Hurricanes are very large-scale rotating winds, typically hundreds of miles across. By definition, hurricane wind speeds exceed 73 mph. Hurricanes are important for coastal DOE sites, but not for ones interior to the continent, as hurricanes typically do not reach inland more than a few hundred miles. For any type of wind, whether straight or rotating, a building is small compared to the size of the area affected by the

wind, and the response of the building is the same. A distinction is made between different types of wind because of the differences in the hazard curves, which show the wind speed as a function of the annual probability of exceeding that wind speed.

Wind speeds for straight winds are measured in terms of peak gust speeds and fastest-mile winds. The latter type is defined as the greatest speed of any "mile" of wind measured during a specified period such as 1 hr, 1 day, 1 month, or 1 year. The largest sustained wind is equal to the fastest-mile wind for the selected period. A peak gust, on the other hand, is the highest instantaneous 3-sec gust wind speed recorded during the specified period.

An interim advisory issued by the DOE Office of Nuclear Safety Policy and Standards<sup>23</sup> to address the issues of straight winds and tornadoes reflects the latest DOE position and should be used. The fastest-mile wind speeds shown in DOE-STD-1020<sup>3</sup> were replaced by "peak gust" wind speeds. Table 3-2, contained in the attachment to this advisory, shows the recommended wind speeds for PC 1 through PC 4 for most sites within the DOE complex.

The performance goals established for PC 1 and PC 2 are met by model codes or national standards. Since model codes specify straight winds at probabilities greater than approximately  $1 \times 10^{-2}$ , tornado design criteria are specified only for SSCs that are designated as PC 3 and higher, where hazard exceedance probabilities are less than  $1 \times 10^{-2}$ .

All wind speeds are 3-sec gusts, which is consistent with the American Society of Civil Engineers (ASCE) 7<sup>24</sup> approach. Design tornado wind pressures on SSCs should be used with Exposure Category C, regardless of the actual terrain roughness. For SSCs in PC 3 and PC 4, it is important to determine whether tornadoes should be included in the evaluation based on geographical location and historical tornado occurrence records. Site-specific tornado hazard assessments are available for most DOE sites, and a quantitative approach should be taken. Details of the approach are presented in Appendix D of DOE-STD-1020.<sup>3</sup>

The weakest link in the load path of an SSC will determine the adequacy or inadequacy of the performance of the SSC under wind load. As a result, evaluation of the existing SSCs normally should focus on the strengths of connections and anchorages, as well as the ability of the wind loads to find a continuous path to the foundation or support system.

Failure caused by wind and tornado is a progressive process, initiating with an element failure. Once the initial element failure occurs at the lowest calculated wind speed, the next event in the failure sequence can be anticipated. All obvious damage sequences should be examined for progressive failures. Once the postulated failure sequences are identified, the SSC performance is compared with the stated performance goals for the specified PC.

As mentioned above, damage to facilities can arise from both wind impacts (pressure changes) and airborne missiles driven by the wind. Coats and Murray<sup>25</sup> relate the wind speed to missile speed for a variety of missiles, as shown in **TABLE 9.2** and **FIGURE 9.20**. The four missiles considered by Coats and Murray are (1) a timber plank (4 in. by 12 in. by 12 ft, 139 lb); (2) a 3-in. diameter standard steel pipe (10 ft long, 75.8 lb); (3) a utility

The PCs for facilities are related to the exceedance probabilities for the NPH events, as discussed above. In the case of wind, the PCs are also related to missile penetrations. These are given in

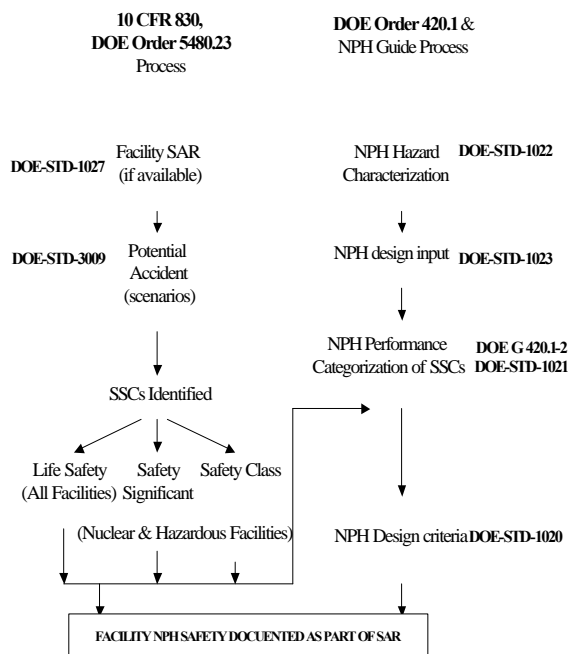


Figure 9.20 – Natural phenomena design hazards design input

pole (13.5-in. diameter; 35 ft long, 1,490 lb); and (4) an automobile (4,000 lb). Obviously, heavier objects and objects with a smaller surface-area-to-volume ratio would have less speed in the wind.

DOE-STD-1020<sup>3</sup> and are summarized in **TABLE 9.3**. This DOE standard should be consulted to determine the wind speeds that correspond to the various PCs for a given site.

Table 9.2 – Windborne Missile Velocities (mph)

WIND SPEED (mph)	MISSILE TYPE			
	Timber Plank	3" Diameter Pipe	Utility Pole	Automobile
100	60	40	0	0
150	72	50	0	0
200	90	65	0	0
250	100	85	80	25
300	125	110	100	45
350	175	140	130	70

Table 9.3 – Summary of Minimum Wind Design Criteria per DOE-STD-1020-2002

PERFORMANCE CATEGORY	1	2	3	4
<b>Straight Wind and Hurricane</b>				
Annual Probability of Exceedance	$2 \times 10^{-2}$	$1 \times 10^{-2}$	$1 \times 10^{-3}$	$1 \times 10^{-4}$
Importance Factor	1.0	1.0	1.0	1.0
Missile Criteria	NA	NA	2 × 4 timber plank 15 lb at 50 mph (horizontal); maximum height 30 ft.	2×4 timber plank 15 lb at 50 mph (horizontal); maximum height 50 ft.
<b>Tornado</b>				
Annual Probability of Exceedance	NA	NA	$2 \times 10^{-5}$ (see Note 1)	$2 \times 10^{-6}$ (see Note 1)
Importance Factor	NA	NA	1.0	1.0
APC	NA	NA	40 psf at 20 psf/sec	125 psf at 50 psf/sec
Missile Criteria	NA	NA	2×4 timber plank 15 lb at 100 mph (horizontal); maximum height 150 ft at 70 mph (vertical).  3-in.-diameter standard steel pipe, 75 lb at 50 mph (horizontal); maximum height 75 ft at 35 mph (vertical).	2×4 timber plank 15 lb at 150 mph (horizontal); maximum height 200 ft at 100 mph (vertical).  3-in. diameter standard steel pipe, 75 lb at 75 mph (horizontal); maximum height 100 ft at 50 mph (vertical).  3,000 lb automobile rolls and tumbles at 25 mph.

Note: These values are for APC and tornado missile criteria are minimum and need to be revisited after new tornado hazard curves currently being developed using the Lawrence Livermore National Laboratory methodology are available.

Table 3-3 in DOE-STD-1020<sup>3</sup> lists recommended “straight wind” missile barriers for SSCs categorized as PC 3 and PC 4. Similarly, Tables 3-4 and 3-5 of this standard show recommended barriers for “tornado” missiles for PC 3 and PC 4, respectively. Although wind pressures, APC, and missile impact loads can occur simultaneously, the missile impact loads can be treated independently for design and evaluation purposes.

#### 9.4.4 FLOOD

In accordance with DOE Order 420.1,<sup>1</sup> the flood design and evaluation criteria seek to ensure that safety SSCs at DOE sites satisfy the performance goals described in DOE-STD-1020.<sup>3</sup> The determination of the design basis flood (DBFL) that must be considered in flood design for design of civil engineering systems such as structures, site drainage, roof systems, and roof drainage is addressed in DOE-STD-1023.<sup>7</sup> The criteria specified in terms of the flood hazard input, hazard annual probability, design requirements, and emergency operation plan requirements are described in Chapter 4, Table 4-1, of the DOE-STD-1020.<sup>3</sup> The mean hazard probability are  $2 \times 10^{-3}$  for PC 1 SSCs,  $5 \times 10^{-4}$  for PC 2 SSCs,  $1 \times 10^{-4}$  for PC 3 SSCs, and  $1 \times 10^{-5}$  for PC4 SSCs.

Flooding occurs when the rate of water entry into an area or facility exceeds the removal rate. According to DOE-STD-1020,<sup>3</sup> both storm sewers and open channels must be sized to accommodate runoff from the 25-year, 6-hr storm. The potential effects of larger storms (up to the 100-year, 6-hr storm) should also be considered. Flooding is important because it can damage facilities, spread contamination, and potentially lead to a criticality. Flooding may be caused by local heavy rains as well as by distant rains that cause nearby rivers to overflow. An accident analysis should examine the statistics of both heavy rain and river flooding. The water load on roofs is also a concern during periods of heavy precipitation. If drainage is blocked, ponds could form on flat roofs and possibly cause structural failure. For example, a pond 1,000 ft<sup>2</sup> in area (e.g., 25 by 40 ft) and 2 in. deep weighs over five tons. This may be enough to breach a roof.

Because floods have a common-cause impact on SSCs located in proximity to one another, the design basis for the most critical SSC may govern

the design for other SSCs or for the entire site. Therefore, it may be more realistic economically and functionally to develop a design strategy that satisfies the performance goals of the most critical SSC and, simultaneously, that of other SSCs. Hardening a site by constructing a levee system may be more feasible for a specific site, thereby protecting all SSCs.

Flood hazard assessment consists of identifying sources of flooding (e.g., rivers, lakes, local precipitation) and the individual associated flood hazards (e.g., hydrostatic forces, ice pressures, hydrodynamic loads). On rare occasion, an individual SSC or the entire site may be impacted by multiple sources of flooding and flood hazard. DOE-STD-1023<sup>7</sup> presents guidelines for conducting a probabilistic flood hazard assessment. As a part of such a probabilistic assessment, an evaluation of uncertainty is also performed. The design basis flood events that must be considered are shown in **TABLE 9.4**. Flood evaluation and protection for nuclear power plants are covered by USNRC Regulatory Guides and the USNRC’s “Standard Review Plan.”<sup>11</sup>

Table 9.4 – Design Basis Flood Events

Primary Hazard	Case No.	Event Combinations
<b>River Flooding</b>	<b>1 Peak flood evaluation</b>	<b>Table 4-2, Chapter 4</b>
	<b>2 Wind waves</b>	
	<b>3 Ice forces</b>	
	<b>4 Erosion, debris, etc.</b>	
<b>Dam Failure</b>	<b>1 All models</b>	<b>DOE-STD-1020</b>
	<b>2 Wind waves</b>	
	<b>3 Erosion, debris, etc.</b>	
<b>Local Precipitation</b>	<b>1 Site runoff</b>	<b>DOE-STD-1020</b>
	<b>2 Ponding on the roof</b>	
	<b>3 Rain and snow</b>	
<b>Storm Surge, Seiche</b> (due to hurricane, seiche, squall lines, etc.)	<b>1 Tide effects</b>	<b>DOE-STD-1020</b>
	<b>2 Wave action</b>	
<b>Levee or Dike Failure</b>	<b>1 Overtopping</b>	<b>DOE-STD-1020</b>
<b>Snow</b>	<b>1 Snow and drift - Roof</b>	<b>DOE-STD-1020</b>
<b>Tsunami</b>	<b>1 Tide effects</b>	<b>DOE-STD-1020</b>

Limited flood hazard assessments for some DOE sites have been conducted. Flood loads are assessed for the DBFL on an SSC-by-SSC basis. If the hazard annual probability for a primary flood hazard is less than the design basis hazard annual probability for a given PC, as mentioned above, it need not be considered a design basis event. For example, if the hazard annual probability for PC 1 is  $2 \times 10^{-3}$  per year, failure of an upstream dam need not be considered if it can be shown that the mean probability of flooding due to dam failure is less than  $2 \times 10^{-3}$ .

The strategy of hardening an SSC or site and providing emergency operation plans is secondary to siting facilities above the DBFL level because some probability of damage does exist and, as a result, SSC operations may be interrupted. Flood mitigation systems (e.g., exterior walls, flood-proof doors, etc.) must be considered in accordance with the requirements specified in the applicable regulations.

Unlike design strategies for seismic and wind hazards, it is not always possible to provide a margin in the flood design of an SSC. When a site is inundated, it will cause significant disruption. Under these circumstances, there is no margin as the term is used in the structural sense. Therefore, the SSC must be kept dry, and operations must not be interrupted to satisfy the performance goals. Refer to DOE-STD-1020<sup>3</sup> for further details.

#### 9.4.5 LIGHTNING

DOE facilities have been struck by lightning numerous times, causing equipment damage and adversely affecting facility safety and operations. At any given time, some 2,000 thunderstorms are occurring around the world, creating approximately 100 lightning strikes every second. In North America, 16 out of 20 accidents involving petroleum product storage tanks are due to lightning strikes.

Lightning is a high-current electrical discharge in the atmosphere with a path length typically measured in km. The electrical currents from lightning range from one to hundreds of kA. The upper one-percentile current (99 percent of all lightning flashes have a lower current) has been determined to be about 200 kA; this is identified (by lightning scientists) as the severe threat level. The median (50th percentile) value lies in the 20- to 30-kA range. Temperatures may reach 30,000 degrees Kelvin, and can travel at 35,000 to 100,000 km/sec.

It is important to assess the severity and frequency of lightning strikes for several reasons. Lightning can cause a fire, a breach in a building, sensor failures or false alarms, communications and electronic component failures, and power failures that give rise to other system failures.

Lightning data for a specific DOE site may be found in the draft DOE standard entitled "Lightning Hazard Management Guide for DOE Facilities."<sup>8</sup> This draft standard has not yet been finalized, however, it addresses the basics of lightning protection within the DOE complex. More general data is also given in the isokeraunic map of the United States given in the "Lightning Protection Code," National Fire Prevention Association (NFPA) 780.<sup>26</sup> Hasbrouck<sup>27</sup> presents a methodology for estimating the density of lightning flashes at a given location, based on the number of thunder days per year and the latitude of the site. The probability of lightning striking a particular object located on the earth (ground) is found by multiplying the object's lightning-attractive area by the local ground-flash density (lightning strikes to ground per km<sup>2</sup> per year).

For flat terrain without buildings or other structures, the probability of a lightning strike is the same throughout the area. Structures, however, especially tall ones such as stacks, water towers, and power poles, attract lightning and increase the probability of a strike at those locations, thus decreasing the probability at other nearby locations. These taller structures thus provide some protection for the shorter structures nearby. The "circle of protection" offered by a tall structure depends on its height and on the peak current in the lightning strike. The higher the structure, the larger the circle of protection. As a rule of thumb, for a medium-current strike,

the radius of the circle of protection is equal to the height of the grounded lightning attractor. This is not valid for all lightning, however, as the radius of the circle of protection also depends on the current in the lightning strike—the larger the current, the larger the circle of protection. A building that may be protected by a larger nearby structure for a high-current lightning strike may not be protected from a lower-current strike. Elevated conducting wires that are horizontal and grounded can also protect facilities below them. Power lines, therefore, could be considered to provide some protection for certain buildings. In general, the stacks, water towers, and power lines of a site offer protection for only a small portion of a site.

Lightning strikes are of great concern to facility managers during the late spring, summer, and early fall. A review of the DOE Occurrence Reporting and Processing System database revealed that 89 percent of lightning-related events occurred during the second and third quarters of the year.

Lightening protection equipment can degrade over time or after suppressing numerous strikes. The degraded equipment can suddenly fail without warning. Deficiencies such as failed surge arrestors or degraded insulation can cause ground faults and electrical distribution system failures. If a particular facility is not protected, the expected number of lightning strikes per year can be found by multiplying the footprint area of the facility by the lightning strike density. If NFPA-specified lightning protection is provided, the likelihood of lightning damage is, of course, greatly reduced.

Risk analysis should consider the consequences of a lightning strike and its likelihood of occurrence. DOE complex sites such as Sandia National Laboratory, the West Valley Site, Fernald, Hanford, the Savannah River Site, and Pantex are a few of the sites where damaging lightning incidences have been reported. The risk for facilities that contain high-energy systems or components such as explosives (e.g., Pantex) would be elevated because of the potential damage from a detonation. Instruments and control systems at many facilities are also vulnerable to damage and lightning-induced malfunction. Brief over-voltages caused by lightning strikes and man-made transient voltages can immediately destroy

low-power solid state components such as computer chips, or can weaken them to the point that they fail months after a lightening event.

Not every lightning strike is damaging. The amount of damage depends on the amount of current in the return stroke, the magnitude of any continuing current, and the susceptibility of the target to lightning damage. Electronic equipment, for example, is more susceptible to failure from a lightning strike than a concrete pad is to fire damage. The main danger to a site from lightning is from fire, as fire can potentially lead to a release of radioactive or chemically hazardous material. Lightning-induced fire can be caused in several ways. Examples are listed below.

- Fire can be started in dry combustible material such as a wooden structure or dry grass by the weak “continuing current” between lightning strokes. About 20 percent of lightning strikes have a continuing current large enough to start such a fire.<sup>28</sup> The magnitude of the peak current is not relevant here, as the return stroke is too brief to start a fire. For lightning to start a range fire, the range grass has to be dry. It is unlikely, therefore, that a range fire would start during a rainstorm.
- A lightning strike on a building can induce large currents in the electrical wiring in the building. It is possible that the high current will cause a breakdown in both the insulation on the wiring and the insulation provided by the air, causing an electrical arc to form between the wire and a nearby grounded object. A follow-on current from the electrical circuit would then sustain the arc and could continue for many seconds or even minutes, long after the lightning strike is gone. Combustible material in the immediate vicinity could then be ignited. Although arcing is more likely with larger-current strikes, any magnitude of strike could produce it. To be conservative, all lightning strikes on a building should be considered.
- A lightning-induced spark in the building could ignite volatile gases from rags damp with cleaning fluids. This could occur with a lightning strike of any magnitude current.

Damage to electronic components from lightning strikes generally can be ignored for safety analyses because such damage is usually not associated with the release of radioactive or chemically hazardous materials.

## 9.5 DEEP-BED SAND FILTERS

Deep-bed sand (DBS) filters have been used in the ventilation and process exhaust systems of radiochemical processing facilities since 1948. The major attractions of DBS filters include large dust-holding capacity, low maintenance requirements, inertness to chemical attack, high heat capacity, fire resistance, and the ability to withstand shock loadings and large changes in air stream pressure without becoming inoperative. The disadvantages of DBS filters include high capital cost; large area; high pressure drop and power cost; uncertainties in selection, availability, grading, and handling of suitable sands; and issues with disposal of the spent unit.

DBS filters are deep (several feet thick) beds of rock, gravel, and sand, constructed in layers graded with about two-to-one variation in granule size from layer to layer. Airflow direction is upward, and granules decrease in size in the direction of airflow. A top layer of moderately coarse sand is generally added to prevent fluidization of finer sand. The rock, gravel, and sand layers are positioned and sized for structural strength, cleaning ability, dirt-holding capacity, and long life. A cross-section of a typical DBS filter is shown in **FIGURE 9.21**. Ideally, the layers of larger granules, through which the gas stream passes first, remove most of the larger particles and particulate mass, and the layers of finer sands provide high-efficiency removal. Below the fixed bed of sand and gravel is a course of hollow tile that forms the air distribution passages. The filter is enclosed in a concrete-lined pit. The superficial velocity is around 5 fpm, and the pressure drop across seven layers, sized from 3 1/2 in. to 50 mesh, is from 7 to 11 in.wg. Collection efficiencies up to 99.98 percent [determined by in-place test with polydisperse 0.7-number medium diameter (NMD) test aerosol have been reported.<sup>33</sup> The approximate capital cost of a sand filter is \$300 per cfm in 2001 dollars.